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14. ABSTRACT

This report describes the purchased equipment to establish two laboratories at the Ohio State Univ. for the fabrication of a novel class of periodic assemblies (PAs) intended to emulate anisotropic media. Such media have already been shown to lead to novel modes, leading to high gain antennas and much smaller RF components. In essence, the purchased equipment are intended to demonstrate a new paradigm in material development for RF applications. The developed labs are (a) Low Temperature Co-fired Ceramics facility in the Dept of Electrical and Computer Engineering, and (b) a Robocasting/Inkjet facility in the Dept. of Materials Science and Engineering. These facilities became operational as part of this effort for a total cost of $1,046,078 ($671,078 in equipment and $375,000 in lab renovations). The AFOSR funding was $350,258. RF characterization equipment were also acquired for collaboration with the Univ. of Texas-San Antonio. Some textured and periodic assemblies emulating anisotropic media were already fabricated and used to demonstrate the novel properties of such media.

15. SUBJECT TERMS
Low Temperature Co-Fired Ceramics, Robocasting, Inkjet, Periodic assemblies, Anisotropic media, High gain antennas, Photonic crystals, Degenerate bandedge

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Introduction

This DURIP was aimed at developing a laboratory to fabricate a novel class of periodic assemblies (PAs) emulating anisotropic media. Such media have already been shown to lead to novel modes that result in high gain antennas and much smaller RF components. This equipment will demonstrate for the first time, a new paradigm in material development for RF applications and possibly a new direction in designing RF components and devices with superior performance. Moreover, this equipment will allow (for the first time) the interaction of material developers and fabrication scientists with RF designers to realize and exploit the potential of the new PAs. Concurrently, measurements will be performed in our world-renowned RF and antenna measurement facilities. Thus, the requested equipment enhances existing computational, measurement and fabrication facilities.

Layered, textured as well as 3D anisotropic media can now be fabricated with the acquired equipment. Also, the same equipment can be adapted for futuristic 3D electronics where each layer/laminate can be printed as desired prior to being stacked an assembled as part of a 3D structure.

The process is shown below and our acquired equipment as part of this DURIP have allowed us to implement this unique process. More importantly, and as shown in Figure 2, we have already used some of the equipment to fabricate sample PAs whose performance led to significant Bandwidth x Gain improvements. In fact, as shown the new crystal assembly (to the left of Figure 2 and entitled DBE-DRA) is very close to the optimum Bandwidth x Gain curve.

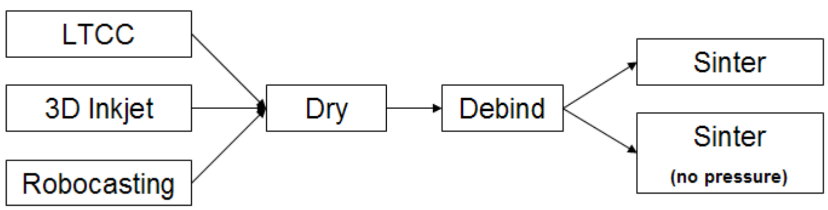


Figure 1. System Flowchart for MPC fabrication.

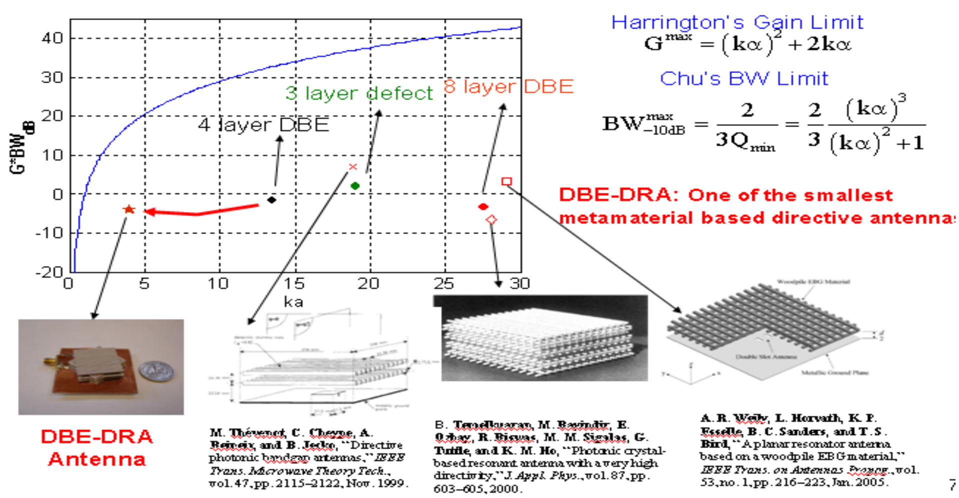


Figure 2. Comparative performance of the recently fabricated DBE antenna using the PAs emulating volumetric anisotropy; This chart verifies the superior performance of the novel modes and the need for the purchased equipment.

Below we describe the purchased equipment, cost and any variations in our purchases. Nearly all equipment are installed and operational. Following the proposal outline, 3 sets of equipment (2 labs and supporting measurement equipment are described below.

Equipment Summary

1. Low Temperature Co-fired Ceramics (LTCC) Fabrication Equipment with Dicing	**Budget:** $292,082 **Actual:** $278,767+ $50,000 Clean room Total Actual: $330,767
2. Robocasting/3D Inkjeting/Hot Pressing	**Budget:** $311,900 **Actual**: $313,311 for equip + $325,000 in Lab renovations
3. High Resolution Microwave Vector Network Analyzer	**Budget:** $96,534. **Actual:** $79,000
Total Cost (all equipment + Lab Renovations):	**Total Actual=$671,078+375,000 =$1,046,078**
Sponsor Cost (all equipment)	**$350,258**

Figure 3. Photos of the LTCC Laboratory in the enclosed Clean Room

As already noted, the purchased equipment were in 3 sets.

- **Set 1 (see Table 1): Equipment for the LTCC Laboratory**

This lab is now complete and mostly operational as depicted above in Figure 3. The summary of purchased equipment is given in Table 1 below. This table is the same as in the DURIP proposal. The left column indicates whether the proposed equipment was purchased and its status. With only one exception, all equipment were purchased as planned and are mostly installed. The following change in equipment was appropriate and necessary:

- The automated screen printing machine was found unnecessary after visiting a similar LTCC lab at Harris Corp. Thus, we only kept the manually controlled screen printed listed in the 2nd row of Table 1.
- Instead of the automated screen printed, we purchased an RF analyzer for the LTCC lab.
- An additional $50,000 (from the PI discretionary funds) were also used to enclose the LTCC lab in a Clean Room (see Fig. 3). This was found necessary after discussions with users of similar machines.

Of the 10 pieces being purchased, only 2 still need to be installed and be brought to full operation. Specifically, we are just in the process of installing the new compressor feeding pneumatic into the clean room. Also, the screen printer and isostatic laminator are in the process of being installed. All other items are operational.

- **Set 2 (see Table 2): Robocasting and Inkjet Equipment**

This equipment were purchased as planned (see Table 2) to support manufacturing activities in the Inorganic Materials Science group (Prof. Verweij) and consisted of the following

In all, 4 major equipment were purchased as listed below

	Cost to AFOSR
1. 3D ink jet printing system:	$30K
2. Robocasting system:	$40K
3. Atmosphere and rate-controlled drying furnace:	$26.3K
4. Atmosphere-controlled hot press:	$59.65K

The total cost to AFOR was $156,000 (as planned). The $1 to $1 cost-sharing brought the total equipment cost to $313,311 (very much as planned). However, additional cost-sharing was added from faculty funds and from the State of Ohio Wright Center for Innovation Fund in the amount of $325,000. These additional funds were used for lab area renovations associated with the installation of the equipment. The detailed equipment status is given later.

- **Set 3 (see Table 3): RF Measurement Equipment**

The cost of this set was $96,000 ($1 to $1 cost-shared).
The key components were

Agilent N5230A vector network analyzer (10MHz to 20GHz),
Agilent 83020A microwave amplifier with 27 dB gain over the 2-26 GHz range.
Newport IMS600 translation stage with spatial resolution of 1 um

These equipment were sent on loan to Prof. Chabanov at the Univ of Texas-San Antonio so that he can carry out the experiments listed later

Overall, with the new lab area renovations (for set 1 and set 2 equipment) of $375,000 for the two labs (LTCC and Robcasting/Inkject), the expended dollars for the purchase and housing of this equipment comes $671,078 (equipment) +375,000 (lab renovations) =$1,046,078. Of this, the AFOSR contributions were $350,258/00

Table 1: Low Temperature Co-fired Ceramics (LTCC) Equipment with quoted prices from proposal

Equipment	Vendor	Item	Contact	Tel.	Full ($)	Disc. ($)
Puncher	T-Tech	QC-HF	Michael Harrington	770-455-0676	18K	17.1K
	T-Tech	Accessories	Michael Harrington	770-455-0676	3K	3K
Screen Printer	Affiliated Manufacturers, Inc.	MSP-485	Paul Hary	908-722-7100	22.5K	21.3K
Microscope (screen printed alignment)	Affiliated Manufacturers, Inc.	Alignment	Paul Hary	908-722-7100	18K	18K
Purchased from projects	Sefar America, Inc.	Masks	Elizabeth Rodriguez	609-613-5000	18.4K	18.2K
Screen Printer Accessories	Affiliated Manufacturers, Inc.	Accessories	Paul Hary	908-722-7100	8K	8K
Not purchased (instead a network analyzer was purchased)	Affiliated Manufacturers, Inc.	Upgrade to automated printing	Paul Hary	908-722-7100	39K	39K
Isostatic Laminator	Pacific Trienetics Corporation	IL-4000 8”	Winston Tan	714-484-8015	69.8K	62.8K
Polishing/Hot Press	Pacific Trinetics Corporation	Accessories	Winston Tan	714-484-8015	10K	9K
Collating Tool Purchased from Projects	Pacific Trinetics Corporation	Collation	Winston Tan	714-484-8015	10K	10K
Debinding/ Sintering Furnace	Applied Test Systems	Box Furnace	Patti McGee	724-283-1212	10K	9.5K
Sectioning Machine	Aremco	5255	Peter Schwartz	845-268-0039	46.2K	46.2K
Green Tape (part of Puncher)	Electro-Science	LTCC tape	James Ianella	610-272-8000	30K	30K

Table 2: **Quotations and Prices for Robocasting, 3D Inkjet, Drying and Hot Press.**

			Supplier/quote	Contact	Tel.	Full ($)	Disc. ($)
3D ink jet printing, including PC			Xaar & Vivid	Bill Leach	210-655-6667	70K	60K
Robocasting, including PC			3D Inks	Jim Smay	405-744-3320	90K	80K
Atmosphere and rate-controlled drying furnace.	Furnace	1	ATS	Robert Antolik	724-283-1212	15K	15K
	Temperature Transmitter	7	Acromag	Judy Schellie	248-624-1541	3.2K	3.2K
	Power controller	6	Eurotherm	Garry Bock	513-353-9955	9.2K	8.7K
	Mass flow controller	4	Brooks Instr.	Howard L. King	513-792-0393	6.4K	6.4K
	Baratron	2	MKS	James T. Rushin	724-969-2520	2K	1.9K
	H_2O sensor	2	Vaisala	Steve Santoro	781-933-4500	4K	4K
	Weight sensor	1	Denver Instrument	Donna Redmond	800-321-1135	3.5K	3.4K
	PC Rack	1	Miscellaneous	N. Cheng	800-872-4547	10K	10K
Atmosphere -controlled hot press.	Frame	1	Instron	Bill Granger	513-934-1484	85K	75K
	Furnace	1	ATS	Robert Antolik	724-283-1212	15K	15K
	Temperature transmitter	2	Acromag	Judy Schellie	248-624-1541	1.1K	1.1K
	Power controller	1	Eurotherm	Garry Bock	513-353-9955	1.5K	1.5K
	Mass flow controller	2	Brooks Instrument	Howard L. King	513-792-0393	3.2K	3.2K
	Baratron	1	MKS	James T. Rushin	724-969-2520	1K	1K
	O_2 sensor	2	Ametek	Donald Athey	412-828-9040	12.5K	12.5K
	PC Rack	1	Miscellaneous	Nicky Cheng Stewart Pitchford	800-872-4547 614-761-3177	10K	10K

Table 3: High Resolution RF Measurement Equipment Prices (est. cost $96,534)

Agilent Vector Network Analyzer(VNA)		**Vendor/web site**	**Disc. ($)**
N5230A PNA-L Network Analyzer, 0.01 to 20 GHz (option 220/225)	1	Agilent, www.agilent.com	$52,757.82
83020A MW Amplifier, 2-26.5 GHz, 27dB gain	1	Agilent	$20,328.00
87422A Power Supply	1	Agilent	$1,183.20
N4691B MW Electronic Calibration Module	1	Agilent	$7,922.40
Other**	2	Agilent	$4,492.00
TOTAL FROM AGILENT			**$84,725.02**

**11500F Cable Assembly(2): $1958.4; 82357A USB/GPIB Interface(1): $399.20; 1250-1741 Adapter(2): $176.

POLARIZER		**Vendor/Contact**	**Disc. ($)**
Microwave Adjustable Polarizer (RH, LH, and L Polarizations), Conical Horn, Tapered Mode Transition and Connectors	2	Millimeter Products Mark Smith: (603) 569-0004	**$4,300.00**
TRANSLATION AND MOTION CONTROLLER		**Vendor/Contact**	**Disc ($)**
IMS600PP Translation Stage	1	**Newport Corp,**	$5,104.00
ESP300-1NN111 Motion Controller	1	James Fisher: (949) 253-1692	$2,405.00
TOTAL FROM NEWPORT Corp.		www.newport.com	**$7,509.00**

Overview of Purchased LTCC Equipment

Overview

The purchased equipment to support the Low Temperature Co-Fired Ceramics (LTCC) Lab Development (Profs. Reano and Volakis) consisted of the following:

Item:		DURIP cost:
1.	Mechanical puncher	$30,985.00
2.	Screen printer	$23,480.88
3.	Isostatic laminator	$27,375.00
4.	Debinding and sintering furnace	$7,713.26
5.	Sectioning Machine	$4,316.96
6.	Polishing System	$8,299.97
7.	Network Analyzer	$24,800.31
8.	Hot plates	$800.73
9.	Microscope	$9,543.94
10.	Mounting press	$2,775.50

The amounts shown were substantially leveraged by a $70,037.32 cash match from OSU, and a $68,639.65 cash match from the Ohio Board of Regents. This combined match is further referred to as "Ohio match", and brought the total budget to $278,768.50. We also added $52K from Prof. Reano's startup, Prof. Volakis' Chope Chair fund, and ElectroScience Discretionary Account for a class 100 clean room, heavy equipment moving cost, lab renovations to accommodate all pneumatic and electrical requirements of equipment, a new compressor, pneumatic and water lines, a vacuum sealer, and lab supplies.

The low temperature co-fired ceramic (LTCC) fabrication process entails sample preparation, via/cavity forming and filling, conductor screen printing, stacking, laminating, de-binding, and sintering. In order to achieve the electrical performance enabled by material structures realized in this process, a low particulate controlled laboratory environment is required.

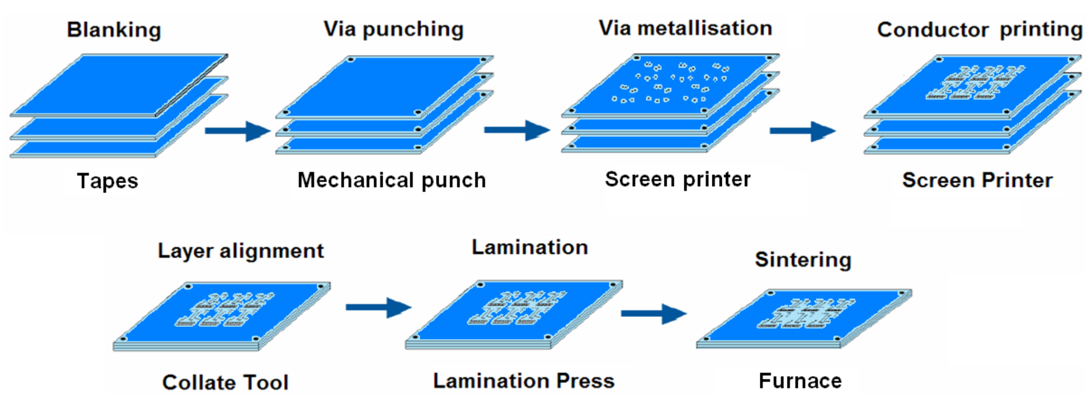
The Clean Air Product 591 modular clean room is a free standing, rigid wall, modular, prefabricated laboratory system that is designed to provide the required low particulate controlled laboratory environment. The rigid wall design allows the clean room to operate at higher internal pressures than may be found in other types of cleanroom systems, enabling the

required low particulate count. This pressure is adjusted through variable wall dampers that regulate the flow of air out of the room that controls the internal room pressure.
This equipment purchase is motivated by a need to realize material structures designed under an on-going Air Force MURI (FA9550-04-1-0359) effort. A new class of periodic assemblies (PAs) were designed under this MURI and shown to demonstrate significant antenna gain (over 25dBi at times). The PAs, referred to as Magnetic Photonic Assemblies or “Crystals” (MPCs), include a magnetic layer in their construction that must also be of low loss at UHF frequencies to realize their potential. A goal is to therefore to find low-cost methods to develop anisotropic layers using low loss stacked tapes, volumetric mixtures and low loss magnetic layers. Fabrication of the available PA and MPC designs will make 'large' strides in realizing the potential of these materials for all sorts of Radio Frequency devices, including miniature antenna arrays and related front end related systems.

The equipment system described in this purchasing document enables fabrication of layered media in low-temperature-co-fired ceramic (LTCC) technology to support our existing analytical and computational (as well as design) activity in this area. This equipment will allow (for the first time) the interaction of material developers and fabrication scientists with RF designers to realize and exploit the potential of the new PAs. Concurrently, measurements will be performed in our world-renowned RF and antenna measurement facilities. Thus, the requested equipment enhances existing computational, measurement and fabrication facilities. Moreover, the proposers have significant activity, and career dedication in their respective fields (materials design, fabrication, and measurements). In short, this equipment will provide the closed-loop interaction necessary for the realization of novel materials for a variety of RF and optical applications. The equipment will be co-located with the faculty/student designers to allow for the necessary interaction of fabrication and computation.

The LTCC fabrication process entails tape preparation, via/cavity forming and filling, conductor screen printing, stacking, laminating, de-binding, and sintering. In contrast to thick film technology where sequential printing, drying, and firing of each layer is conducted, LTCC technology processes all layers within a multilayer structure in parallel, resulting in high yield and low cost. Sintering temperatures below 1000 °C also allows for screen printable inks composed of metals such as copper, silver, and gold.

We are in the processes of installing the new compressor which will feed pneumatic into the clean room. The screen printer and isostatic laminator are in the process of being installed. All other items are operational.



Complete In-House LTCC Fabrication Process

B. Equipment

B.1. Mechanical puncher

Item
Unichem UHT MP-4150N
Unichem UHT TP-04 Punch Setting System
Unichem assortment of punches and dies (0.1 mm – 0.2 mm)

DURIP cost	Cash match from OSU	Cash match from Ohio Board of Regents	Total budget
$30,985	$15,490.19	$14,710.63	$61,185.85

Vias and registration holes are created in LTCC using a mechanical punch. Punching precision of at least ±10 μm with a resolution of at least 1 μm is required since LTCC fabrication requires precision alignment of vertically stacked green tapes. A punch area of at least 5.9’ x 5.9’ is required.

The UHT MP-4150N positions a punch and die unit to produce vias and registration holes in LTCC green tape. It has a punch area of 5.9” x 5.9”, a punch holder of 8.8’ x 8.8’, four mountable punch units, a punching precision of ±10 μm, a punching resolution of 1 μm, a punch speed of 600 holes per minute, punch position storage capability of 30,0000 positions, a dust collector, and a control system for punch data communications. The TP-04 is a punch setting system that ensures accurate die positioning, extending the life of the system.

B.2. Screen printer

Item
MSP-485 Screen Printer
u-Lign IV^{TM} - Manual vision alignment system
Laser pointers
Porous stone tool plate
Vacuum pull thru
Vacuum sources
Digital squeege speed display and cycle counter
Spare parts kit

DURIP cost	**Cash match from OSU**	**Cash match from Ohio Board of Regents**	**Total budget**
$23,480.88	$11,738.68	$11,897.19	$47,116.75

Once via and registration holes are formed in LTCC green tapes, the next process involves metallization by via filling and printing. This is accomplished with the MSP-485 screen printer. Via filling is the process in which the via holes formed in the green sheet for conduction between layers are filled with conductive paste. Printing is the process by which a conductive pattern is gap printed on an aligned green sheet. Since multiple layers are required to be aligned to one another, an alignment system is required. This is accomplished with the u-Lign II^{TM} alignment system together with the laser pointers. The porous stone tool plate, vacuum pull through, and vacuum sources hold the tape in place and ensure via filling. A screen print area of at least 8” x 8” is required for application. Independent X, Y, and theta manual adjustment is required. A carriage position repeatability of ±0.0002” is required. A porous stone tooling plate with vacuum pull thru is required for via filling and substrate hold down. Monitoring of the squeege speed and a cycle counter is required for repeatability.

The MSP-485 screen printer has a screen print area of 8" x 8" with independent X, Y, and theta manual adjustment. The u-Lign II^{TM} manual vision alignment system provides adjustable dual croosshairs for precision print image to substrate alignment. The laser pointers aid in camera placement over printing targets. The porous stone tooling plate, vacuum pull thru, and vacuum sources are required for proper via filling and substrate hold down. The carriage position repeatability is ±0.0002”. A digital squeege speed display and cycle counter enable repeatable results.

B.3. Isostatic laminator

Item
Avure Autoclave LIL71010-SS

DURIP cost	Cash match from OSU	Cash match from Ohio Board of Regents	Total budget
$27,375.00	$13,687.50	$13,687.50	$54,750.00

The next step in the LTCC process is collation and lamination. This step prepares the multi-layer structure for binder burnout and sintering through the application of pressure and temperature. Equal pressure and temperature is essential for material uniformity. An isostatic laminator produces equal pressure and temperature in all directions. This method utilizes a lamination chamber filled with heated water and put under pressure. A special bagging material forms around the package and is sealed with the package and fixture plate inside. It is immersed into the chamber and controls allow for controlling the water temperature and pressure settings, along with dwell and hold times for process control. A typical setting for LTCC is 70° C for 5 to 10 minutes at about 5,000-7,000 psi. A workzone at least 7 inches in diameter and 10 inches deep is required.

The LIL71010-SS is rated for operation up to 90 degrees C and 10,000 psi. It has a workzone of 7 inches in diameter and is 10 inches deep. The VM101H performs the bag sealing function prior to insertion of the sample into the isostatic lamintor. The benefit of using an isostatic method is that is ensures equal pressure and temperature are being exerted on all surfaces. The results have shown good dimensional characteristics, no rounding of edges or camber, and no need for lamination dies associated with uneven sheet sizes. With equal pressure being exerted on all sides, package distortion is virtually eliminated. This means an even distribution of shrinkage occurs during firing. Shrinkage problems that can occur from part to part, from uniaxial hot press or platen press lamination, are eliminated. Also, with isostatic lamination, many packages can be processed at the same time within the chamber – speeding up processing time.

B.4. Debinding and sintering furnace

Item
LH 60/13 with C250 Controller
D05 Fan
Second Fan Speed Set Point
Stainless Steel Exhaust Hood
Over Temperature Limit Controller

DURIP cost	**Cash match from OSU**	**Cash match from Ohio Board of Regents**	**Total budget**
$7,713.26	$3,856.05	$2,955.44	$14,524.75

After laminating LTCC, the sample is heated at high temperature to drive off organic constituents (binder removal) and to provide densification (sinter). Chamber dimensions of 400 mm x 400 mm x 400 mm is required for uniform heating of the sample. A maximum temperature of 1000 degrees C is required for sintering. Air flow is required to clear binder. An exhaust hood is necessary for binder removal. Cooling requires a fan at a second speed setpoint. Firing profiles need to be precisely controlled to ensure binder removal and proper sintering.

The LH 60/13 with C250 controller is a laboratory scale electrically heated batch furnace. The controller enables the user to design a firing profile. The D05 Fan allows for air flow within the chamber in order to enable efficient binder removal. The second fan speed set point allows the fan to run at a second speed for cooling. The exhaust hood is used for binder removal. The over temperature limit controller guards against exceeding maximum rated temperatures. The max operating temperature is 1300 degrees C. The inner dimensions are 400 x 400 x 400 mm.

B.5. Sectioning Machine

Item
TechCut 5^{TM} Precision Sectioning Machine
Cam-Lock Holding Device

DURIP cost	Cash match from OSU	Cash match from Ohio Board of Regents	Total budget
$4,316.96	$2,158.15	$2,183.70	$8,658.81

After sintering the LTCC, the sample is sectioned to size. The TechCut 5^{TM} is a precision sectioning machine designed to cut a wide variety and size of materials. The microprocessor based system allows a stepper motor to control sample feed-rate, distance, and force, and automatically adjusts feed rate as the cutting condition changes due to varying thickness and/or material differences in the sample. The Cam-Lock holding devices is used to hold the sample.

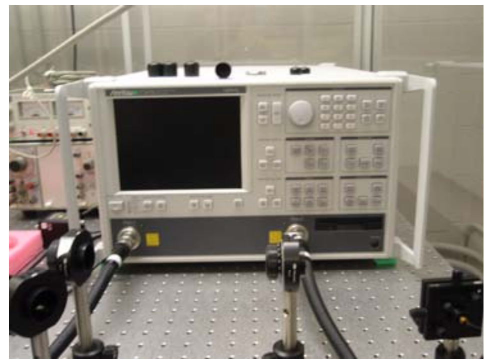
B.6. Polishing System

Item
MultiPrep^{TM} Precision Polishing System
Parallel Polishing Fixture
Cross-Sectioning Paddle
Multi-Purpose Sample Fixture

DURIP cost	Cash match from OSU	Cash match from Ohio Board of Regents	Total budget
$8,299.97	$4,149.36	$4,198.48	$16,647.80

After sectioning the LTCC, precision polishing of the sample surfaces are required for device performance. The MultiPrep™ Precision Polishing System enables precise semiautomatic sample preparation of a wide range of materials. Capabilities include parallel polishing, precise angle polishing, site-specific polishing. The parallel polishing fixture, cross-sectioning paddle, and multi-purpose sample fixture are for sample mounting.

B.7. Network Analyzer



Item
Anritsu 37247D Vector Network Analyzer
SMA/3.5 mm Calibration Kit
K(f) -K(m) Cable, 25 inches (2 each)

DURIP cost	**Cash match from OSU**	**Cash match from Ohio Board of Regents**	**Total budget**
$24,800.31	$12,398.30	$12,310.00	$49,508.61

The material structures realized in LTCC generate large RF electric-fields with the material itself. In order to exploit these high RF field regions, optical techniques will be employed. This vector network analyzer will be integrated with an optical laser source to enable the RF electric-fields to be extracted via optical modulation and demodulation. A 20 GHz bandwidth with 1 Hz resolution is required.

The Anritsu 37347D vector network analyzer operates with a 20 GHz bandwidth with 1 Hz frequency resolution. It includes electronic-to-optical and optical-to-electronic measurements, embed/de-embed application, high stability frequency reference, rear panel IF inputs. The calibration kit is required for accurate measurements. The cables allow the device-under-test to be connected to the vector network analyzer.

B.8. Hot plates

Item
Cole Palmer EW-86576-30 (2)

DURIP cost	Cash match from OSU	Cash match from Ohio Board of Regents	Total budget
$800.73	$400.30	$465.00	$1,666.03

Processing of LTCC samples requires hot plates with stirrers. This is a hot plate with a magnetic stirrer.

B.9. Microscope

Item
Microscope

DURIP cost	Cash match from OSU	Cash match from Ohio Board of Regents	Total budget
$9,543.94	$4,771.25	$4,827.74	$19,142.93

A microscope is required for LTCC sample examination. We require 5x, 10x, 20x, 50x, and 100x magnification with 25% and 6% gray filter transmission, reflection mode, expandability to advanced darkfield and circular differential interference contrast.

The Allied High Tech Axiolmager is a microscope with up to 100x magnification that allows examination of results. Functions include 5x, 10x, 20x, 50x, and 100x magnification with 25%

and 6% gray filter transmission, reflection mode, expandability to advanced darkfield and circular differential interference contrast.

B.10. Mounting press

Item
Techpress 2
1.25" Mount

DURIP cost	**Cash match from OSU**	**Cash match from Ohio Board of Regents**	**Total budget**
$2,775.50	$1,387.54	$1,403.97	$5,567.01

For polishing LTCC, samples need to be mounted. This mounting press mounts the sample on a mold using temperature and pressure. This allows the sample to be positioned securely for polishing. This tool used temperature and pressure to form a mount around a sample in order to prepare it for mounting on the polishing tool.

Robocasting and Inkjet Equipment

These equipment were purchased (see Table 2) to support manufacturing activities in the Inorganic Materials Science group (Prof. Verweij) and consisted of the following:

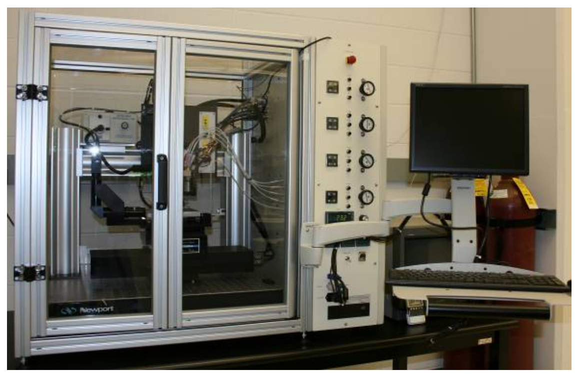
	Cost to AFOSR
5. 3D ink jet printing system:	$30K
6. Robocasting system:	$40K
7. Atmosphere and rate-controlled drying furnace:	$26.3K
8. Atmosphere-controlled hot press:	$59.65K

The amounts shown were substantially leveraged by a $78,157.51 cash match from OSU, and a $78,307.25 Cash match from the Ohio Board of Regents. This combined match is further referred to as “Ohio match”, and brought the total budget to $313,311.22. We also added $73K from a colleagues startup fund, and used $252,979.23 from the State of Ohio Wright Centers for Innovation Fuel Cell (WCIFC) program to purchase more advanced equipment for shared use. During the performance period we realized a major lab renovation to accommodate all equipment. Most purchasing was done by students who were active in related areas. Most are now installed, already used or ready for use.

3D Ink Jet printer

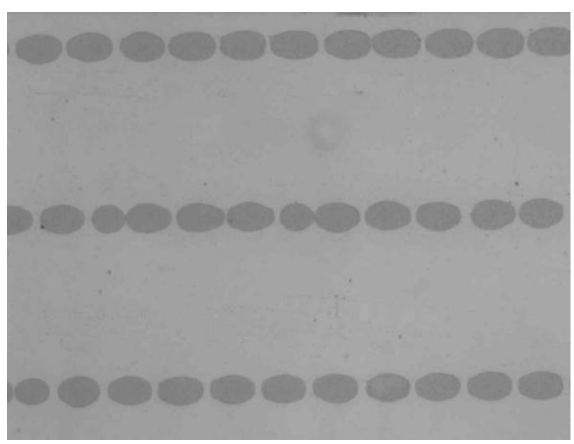
Status: Operational.

Jetlab II printing system is an advanced fluid microdispensing system to fabricate gas sensors based on materials developed through nanotechnology. Stabilized nanoparticle suspensions are printed through a piezoelectric nozzle into a pre-designed pattern under precise speed and pressure control.



Jetlab II printing system.

The JetLab II ink jet printer is now fully operational, see figure**Error! Reference source not found.** and we have already printed the first TiO_2 antenna structures on glass, see figure to the right.



Ink-Jet printed TiO_2 dots of ~20 μm diameter.

We eventually selected a more advanced and more suitable MicroFab JetLab II ink-jet printing system for heavily discounted $133,000. Of this amount $73.000K was provided by colleague P.A. Morris’ startup funds, and we have free access to this shared facility. We used $30,090 from DURIP and $30.000 Ohio match.

Single wafer spin processor

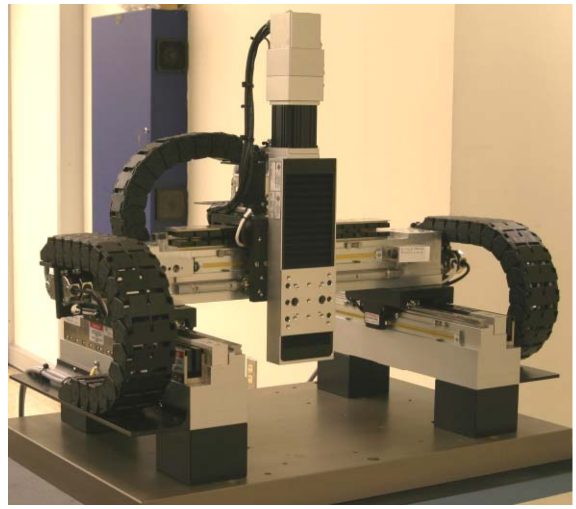
Status: In installation.

A spin coater is used to deposit thin uniform films, from liquid based solutions and suspensions, onto planar substrates of various 2D geometries (circular, rectangular, etc). We use spin coating is used to provide a uniform printing substrate. The spin processor allows sufficient process control to deposit the thin adhesive coatings uniformly on the substrates prior to printing of the 3D structures.

We purchased a Laurell Technologies Corp. Single Wafer Spin Processor for $4,685, of which 2,342.62 from the DURIP budget, and 2,342.38 as Ohio match.

Robocasting system

Status: In assembly.
Robocasting® is an advanced fabrication technique to make complex 3D ceramic structures clean and fast. For our antenna applications, it is required to realize 3D periodic structures with mm details. The Robocasting® system had to be designed and assembled, this took substantially longer than planned. It consists of the following components were purchased:



AGS1000 mechanical bearing gantry system.

- **Aerotech Inc. | AGS1000**.
  Sub-status: Partially installed.
  The advanced mechanical gantry positioning system provides high speed and high accuracy (< 5 μm) motions along all three directions. An incorporated computer pre-programming allows for carrying out pre-designed motion patterns and speeds, see figure to the right
- **Ultra 2400 dispenser and syringes**.
  Sub-status: pending installation.
  The dispensing syringe is to be mounted on the z stage of the AGS1000 and hence follow the motion of the mechanical stage. The ultra 2400 controller regulates dispensing pressure and hence extrusion speed of the ceramic gel for a specific 3D structure.
- **Fritsch Minimill, Pulverisette 23**.
  Sub-status: in use.
  This is a vibrating mill for mixing and grinding precursor powders for the preparation of reproducible, low-loss magnetic ferrite ceramics. These ceramics form an essential magnetic component in MPA designs. The mill uses vertical oscillations with high amplitude to generate a particle size reduction by way of impact and friction between the grinding balls and grinding bowl walls. In addition, the mill is a light weight tabletop model

Fritsch Minimill, model Pulverisette 23.

and holds between 0.1 and 5.0 mL of material, which are typical amounts used in lab and prototype experiments, see figure above.

- **Thinky® ARE-250 gel mixer**.
  Sub-status: in use.
  The mixer is used to produce homogeneous ceramic gels directly from ceramic powders and organic binders. It uses a new method of "non-contact centrifugal mixing" that avoids entrapping bubbles and dramatically improves mixing efficiency.
- **SmartTable®, I-2000 isolators and enclosure**.
  Sub-status: Partially installed.
  The vibration-free (optical) table with active damping is used as the steady base for Robocasting® system to maintain a high accuracy in the mm-scale MPAs, see figure**Error! Reference source not found.**.

SmartTable® and I-2000 isolators.

- **High-speed visual monitoring**
  Sub-status: pending installation.
  The vision system will be used to monitor in real time, the formation process of 3D complex structures under Robocasting®, as well as guidance for feedback control.

Expenditure summary

- Aerotech Inc/Mechanical Bearing Gantry System: $51,270.00
- EFD Inc. Ultra 2400 Dispensing workstation: $10,292.58
- Ahead & Beyond LLC ARE-250-11-E Vacuum-less planetary centrifugal mixer: $10,506.00
- Fritsch Pulverisette 23 Vibrat: $9,499.71
- Fisher Scientific Vacuum Controller; Ultrasonic: $3,552.02
- 1st Vision Inc. JAI Gig-E TMC-2040GE system: $6,708.00
- NEWPORT CORP/Customized Smart Table, I-2000 isolators and enclosure: $18,419.03

Of the total amount of $110,247.34, $54,966.19 was provided from the DURIP budget and $55,281.15 as Ohio match.

Atmosphere and rate-controlled drying

Reactive ion etching system

Status: pending installation.
Reactive ion etching (RIE) allows densification of thin ceramic layers at very low temperature by effectively removing polymers. It largely improves the flexibility of temperature control and resolves, otherwise occurring, thermal stress between different materials.

The Oxford Instruments Inc. Plasmalab 80 Plus has a configuration for etching of SiO_2, SiN and related dielectric materials used in the fabrication of MEMS and Photonic devices. It will be used for fabricating thin dielectric and magnetic layers in MPAs.

The total purchase price was $160,956. Of this amount $112,960 was provided from the State of Ohio Wright Center for Fuel Cells (WCIFC) project; $23,998 was used from the DURIP budget, and $23,998 was provided as Ohio match. Extensive installation of required infra-structure and gas lines has delayed installation. The equipment will be operational soon, see figure to the right.

Plasmalab 80 Plus Compact etching system (left) and heater/chiller unit (right).

CAHN TherMax 500 High Pressure TGA System

Status: operational

The chemical reactivity of as-prepared magnetic or dielectric powders can be analyzed using a high pressure TGA system. Chemical reactions between environment and the samples are monitored from the sample weight change. The TherMax 500 system is equipped with a Thermo CAHN D-110 pressure balance for pressures to 100 bar and temperatures up to 1100°C. In addition, special instrumentation software allows programming of heating/cooling and isotherm segments, and control of the optional gas-switching module. It is currently operational, see figure**Error! Reference source not found.**.

We purchased the Cahn Thermax 500 High Pressure ThermoGravimetric Analyzer from Thermo Fisher Scientific (Asheville) LLC at a heavily discounted price of $124.015. Of this amount $64,100.81 was provided from the WCIFC project, $29,979.13 was used from the DURIP budget, and 29,935.06 from Ohio match.

CAHN TherMax 500 High Pressure TGA System.

Atmosphere-controlled hot press

Status: in use.

In hot pressing high-performance materials are made by application of a combination of programmed heating and pressing at the same time. The application of high pressure during densification can significantly lower the processing temperature, shorten the processing period and enhance the sample quality.

Pressure is applied to a sample via a fixture set from Applied Test System Inc. (ATS), a vendor-designed set of mechanical adapters, pull-rods and rod rams. The fixture is mounted on an Instron 5569 pressing frame, and into a high-temperature furnace, which is also customized and manufactured by ATS, see figure**Error! Reference source not found.**. The hot press has been used to prepare the first functional MPA structure, shown in the figure

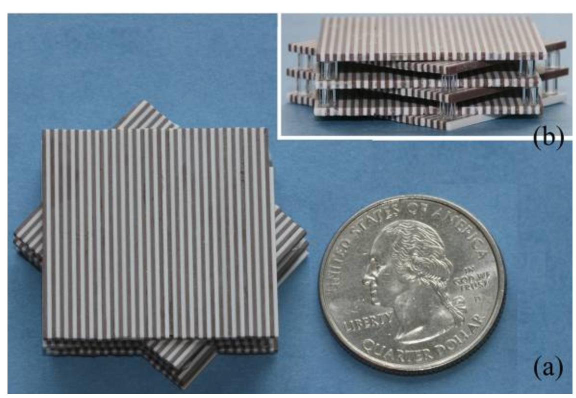
Hot press furnace with pressing fixture.

Expenditure summary

To achieve the definition of processing that we needed for the antenna materials we decided on a hot press system that was much more expensive than originally planned. The following components were purchased:

- Instron Co. 5569 Table Mounted 50 kN Frame: $41,053.75
- Applied Test Systems (ATS) 2404 Temperature Control: $5,928.96
- ATS 3350-CA High Temperature Furnace: $28,935.71
- Applied Test Systems Inc. Upper & Lower Water Cooled Pull Rod Adapter: $21,012.95

Of the total amount of $96,931.37, $75,918.42 from provided from the WCIFC budget, $10,585.46 was provided from the DURIP budget and $10,585.46 as Ohio match.



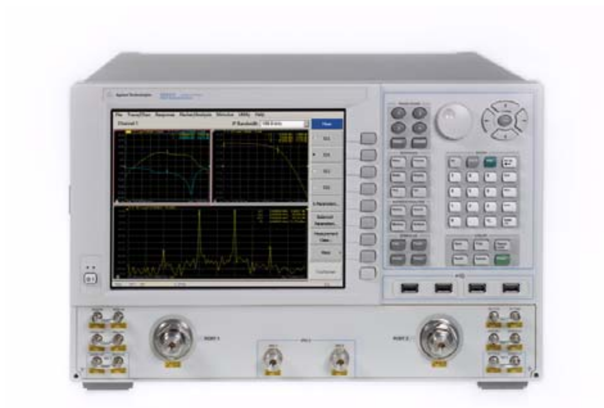
6-layer anisotropic dielectric MPA (a) top view and (b) side view.

Publications

1. L.L. Zhang, G. Mumcu, K. Sertel, J.L. Volakis, and H. Verweij, "Low-loss anisotropic dielectrics at GHz frequency from laminar structures," J. Mater. Sci., **43**(5), 1505-1509 (2008).
2. L.L. Zhang, G. Mumcu, K. Sertel, J.L. Volakis, and H. Verweij, "Low-loss anisotropic dielectrics at GHz frequency from laminar structures," Proceedings TMS 2007.
3. K.Sertel, J.L. Volakis, and H. Verweij, "Periodic Materials and Printed Structures for Miniature Antennas," Proceedings IWAT'07, (2007).
4. LL. Zhang and H. Verweij, "Ceramic Processing for Multi-Material Devices with Complex Geometry," Proceedings IEEE, Hawaii, (2007).
5. M.J. O'Malley, H. Verweij, and P.M. Woodward, "Structural, Thermal, Optical, and Electrical Properties of Li_2MO_3 (M = Ru, Ir, Pt) and Li_3RuO_4," J. Sol. St. Chem, accepted 2008.
6. L.L. Zhang, and H. Verweij, "Fabrication of photonic assemblies for high-gain antennas," Proceedings MS&T, 2007.

L.L. Zhang, K. Shqau, H. Verweij, G. Mumcu, K. Sertel, and J.L. Volakis, "Viable route for dense TiO2 with low microwave dielectric

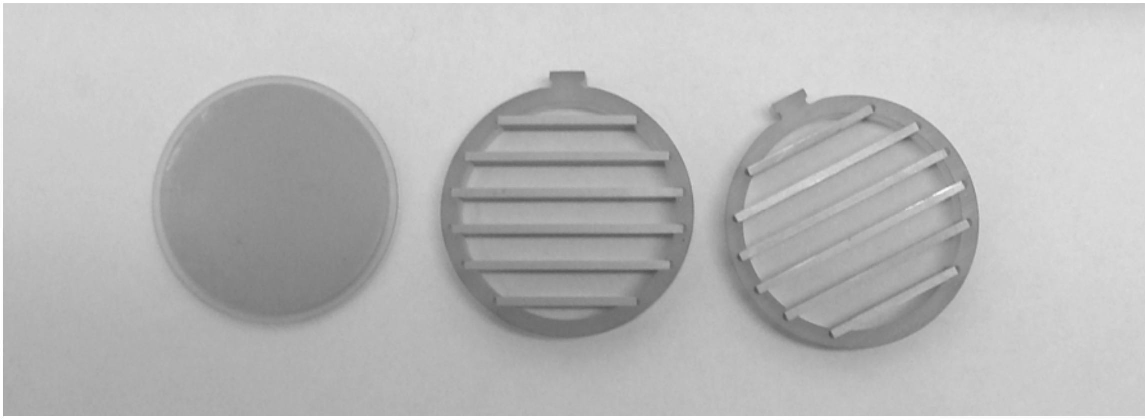
RF Precision Measurement Equipment



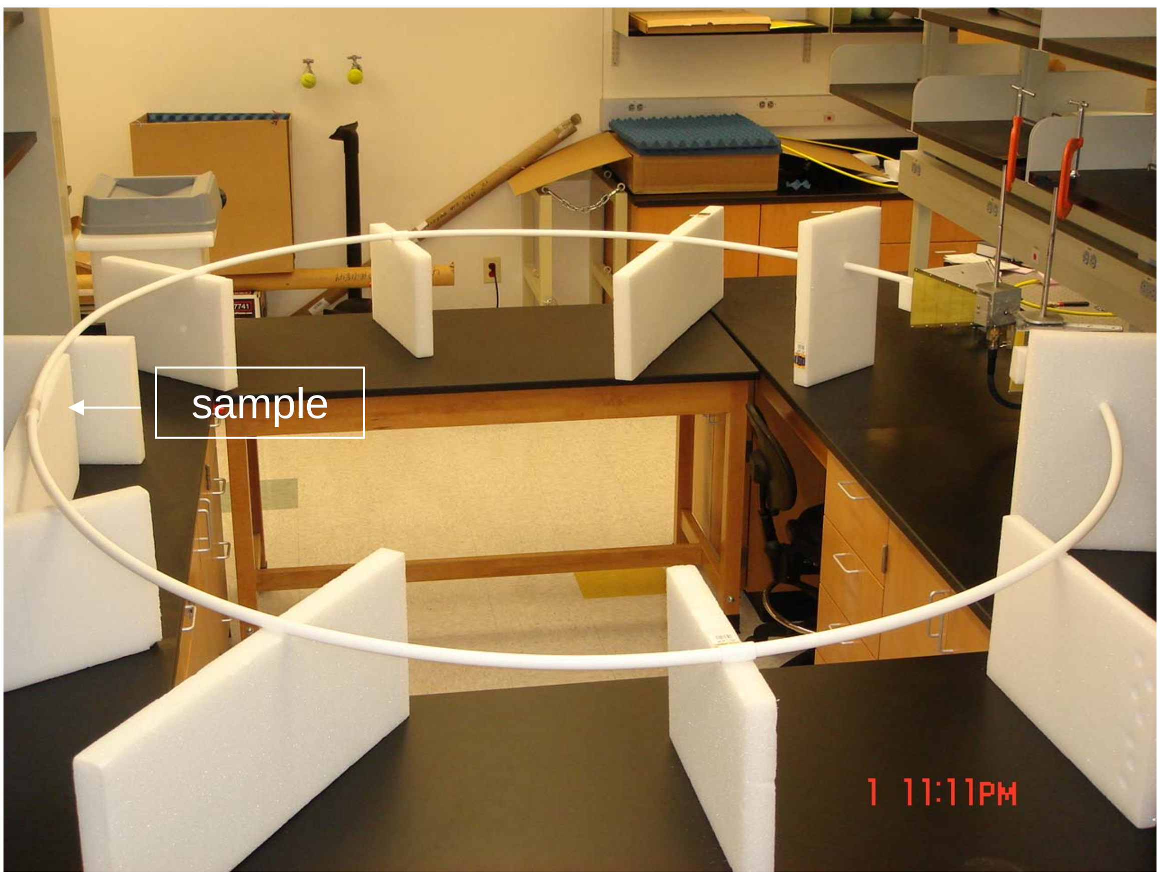
The resonant properties of periodic layered structures with degenerate and split band edge, DBE and SBE, have been demonstrated in microwave measurements in periodic stacks of form-birefringent layers realized in waveguide geometry. Dielectric layers were fabricated of low-loss microwave ceramics in the form of disks. A loop of Teflon rods was employed to deliver microwave radiation to and from the periodic layered samples. Two horns, set to produce radiation of the same polarization, were used to launch and detect the microwave radiation. Field spectra in samples with number of unit cells N ranging from 8 to 17 were obtained with the use of a Hewlett-Packard N5230A vector network analyzer acquired with help of this grant. Once a band-edge transmission resonance was detected for a given N, structure parameters and orientation were adjusted to achieve the highest Q. The resonant character of transmission was further indicated by a sharp peak in the spectrum of group delay. The distribution of microwave intensity within the layered structure was measured by a weakly-coupled probe translated along the structure.

The microwave measurements have confirmed that transmission resonances with exceptionally high Q's can be achieved in the DBE and SBE layered structures, even when the number of layers is not large. A microwave transmission resonance with Q~220 was demonstrated in a SBE periodic stack with N=12. The SBE resonators exhibit a nearly perfect impedance matching at the boundaries. The resonant transmission is nearly unity for any incident polarization, while the resonance bandwidth can be substantially changed with the incident wave polarization. However, a factor-of-5 reduction in values of Q, as compared to simulations, was observed in the measurements, which was attributed to waveguide geometry of the sample. Thus, the current research is aimed to optimize parameters of the structure, in order to improve the resonant properties of the periodic layered structures.

The Agilent N5230A vector network analyzer has a frequency range from 10MHz to 20GHz, resolution of 1 Hz, and up to 16,000 frequency points in the trace. It allows carrying out high-resolution measurements over a wide frequency range in a single sweep. Since the intensity distribution within the layered structure is measured by utilizing an exponentially weak coupling from the outside of the sample, a substantial amplification of the microwave signal without the introduction of substation noise is required. This is provided by the Agilent 83020A microwave amplifier with 27 dB gain over the 2-26 GHz range. The Newport IMS600 translation stage with spatial resolution of 1 um is used to translate the probe along the structure for the intensity distribution measurement.



Picture of the fabricated layers of the periodic layered samples used in the microwave experiment.



Experimental setup for microwave measurements of periodic layered structures.